

FORM PTO-1390 (Modified) (REV 11-2000)		U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE		ATTORNEY'S DOCKET NUMBER <b>A-7769</b>	
TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371				U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.5) <b>10/030128</b>	
INTERNATIONAL APPLICATION NO <b>PCT/EP00/07166</b>		INTERNATIONAL FILING DATE <b>26 July 2000 (26.07.2000)</b>		PRIORITY DATE CLAIMED <b>27 July 1999 (27.07.1999)</b>	
TITLE OF INVENTION <b>METHOD AND DEVICE FOR CORRECTING TOOL POSITION ERRORS IN MACHINE TOOLS</b>					
APPLICANT(S) FOR DO/EO/US <b>Raffaele TOMELLERI</b>					
Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:					
<ol style="list-style-type: none"> <li>1. <input checked="" type="checkbox"/> This is a <b>FIRST</b> submission of items concerning a filing under 35 U.S.C. 371.</li> <li>2. <input type="checkbox"/> This is a <b>SECOND</b> or <b>SUBSEQUENT</b> submission of items concerning a filing under 35 U.S.C. 371</li> <li>3. <input checked="" type="checkbox"/> This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (24) indicated below.</li> <li>4. <input checked="" type="checkbox"/> The US has been elected by the expiration of 19 months from the priority date (Article 31)</li> <li>5. <input checked="" type="checkbox"/> A copy of the International Application as filed (35 U.S.C. 371 (c) (2)) <ol style="list-style-type: none"> <li>a. <input checked="" type="checkbox"/> is attached hereto (required only if not communicated by the International Bureau).</li> <li>b. <input type="checkbox"/> has been communicated by the International Bureau.</li> <li>c. <input type="checkbox"/> is not required, as the application was filed in the United States Receiving Office (RO/US).</li> </ol> </li> <li>6. <input type="checkbox"/> An English language translation of the International Application as filed (35 U.S.C. 371(c)(2)) <ol style="list-style-type: none"> <li>a. <input type="checkbox"/> is attached hereto</li> <li>b. <input type="checkbox"/> has been previously submitted under 35 U.S.C. 154(d)(4).</li> </ol> </li> <li>7. <input checked="" type="checkbox"/> Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3)) <ol style="list-style-type: none"> <li>a. <input type="checkbox"/> are attached hereto (required only if not communicated by the International Bureau)</li> <li>b. <input type="checkbox"/> have been communicated by the International Bureau</li> <li>c. <input type="checkbox"/> have not been made; however, the time limit for making such amendments has NOT expired.</li> <li>d. <input checked="" type="checkbox"/> have not been made and will not be made</li> </ol> </li> <li>8. <input type="checkbox"/> An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).</li> <li>9. <input type="checkbox"/> An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4))</li> <li>10. <input type="checkbox"/> An English language translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).</li> <li>11. <input type="checkbox"/> A copy of the International Preliminary Examination Report (PCT/IPEA/409)</li> <li>12. <input checked="" type="checkbox"/> A copy of the International Search Report (PCT/ISA/210).</li> </ol> <p><b>Items 13 to 20 below concern document(s) or information included:</b></p> <ol style="list-style-type: none"> <li>13. <input type="checkbox"/> An Information Disclosure Statement under 37 CFR 1.97 and 1.98.</li> <li>14. <input type="checkbox"/> An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.</li> <li>15. <input checked="" type="checkbox"/> A <b>FIRST</b> preliminary amendment</li> <li>16. <input type="checkbox"/> A <b>SECOND</b> or <b>SUBSEQUENT</b> preliminary amendment</li> <li>17. <input type="checkbox"/> A substitute specification.</li> <li>18. <input type="checkbox"/> A change of power of attorney and/or address letter</li> <li>19. <input type="checkbox"/> A computer-readable form of the sequence listing in accordance with PCT Rule 13ter 2 and 35 U.S.C. 1.821 - 1.825.</li> <li>20. <input type="checkbox"/> A second copy of the published international application under 35 U.S.C. 154(d)(4)</li> <li>21. <input type="checkbox"/> A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4)</li> <li>22. <input type="checkbox"/> Certificate of Mailing by Express Mail</li> <li>23. <input type="checkbox"/> Other items or information</li> </ol>					

U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.5) <div style="font-size: 1.5em; font-weight: bold;">10/030128</div>		INTERNATIONAL APPLICATION NO. <div style="font-weight: bold;">PCT/EP00/07166</div>		ATTORNEY'S DOCKET NUMBER <div style="font-weight: bold;">A-7769</div>	
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24. The following fees are submitted: <b>BASIC NATIONAL FEE ( 37 CFR 1.492 (a) (1) - (5) ) :</b> <div style="display: flex; justify-content: space-between;"> <div style="width: 80%;"> <input type="checkbox"/> Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO  <input checked="" type="checkbox"/> International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO  <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO  <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4)  <input type="checkbox"/> International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) </div> <div style="width: 15%; text-align: right;"> <div style="font-weight: bold;">\$1040.00</div>  <div style="font-weight: bold;">\$890.00</div>  <div style="font-weight: bold;">\$740.00</div>  <div style="font-weight: bold;">\$710.00</div>  <div style="font-weight: bold;">\$100.00</div> </div> </div> <div style="text-align: center; font-weight: bold; margin-top: 10px;">             ENTER APPROPRIATE BASIC FEE AMOUNT =         </div>				<b>CALCULATIONS PTO USE ONLY</b>  <div style="border: 1px solid black; height: 100px; width: 100%;"></div>	
Surcharge of <b>\$130.00</b> for furnishing the oath or declaration later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492 (e))				<div style="border: 1px solid black; padding: 2px;">\$0.00</div>	
CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	30 - 20 =	10	x \$18.00	\$180.00	
Independent claims	2 - 3 =	0	x \$84.00	\$0.00	
Multiple Dependent Claims (check if applicable). <input type="checkbox"/>				\$0.00	
TOTAL OF ABOVE CALCULATIONS =				\$1,070.00	
<input checked="" type="checkbox"/> Applicant claims small entity status See 37 CFR 1.27). The fees indicated above are reduced by 1/2.				\$535.00	
SUBTOTAL =				\$535.00	
Processing fee of <b>\$130.00</b> for furnishing the English translation later than <input type="checkbox"/> 20 <input type="checkbox"/> 30 months from the earliest claimed priority date (37 CFR 1.492 (f))				\$0.00	
TOTAL NATIONAL FEE =				\$535.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)) The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) (check if applicable). <input type="checkbox"/>				\$0.00	
TOTAL FEES ENCLOSED =				\$535.00	
				Amount to be: refunded	\$
				charged	\$

a. ☒ A check in the amount of \$535.00 to cover the above fees is enclosed

b. ☐ Please charge my Deposit Account No. \_\_\_\_\_ in the amount of \_\_\_\_\_ to cover the above fees  
A duplicate copy of this sheet is enclosed


c. ☒ The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No 08-2455 A duplicate copy of this sheet is enclosed.

d. ☐ Fees are to be charged to a credit card. **WARNING:** Information on this form may become public **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038

**NOTE:** Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO

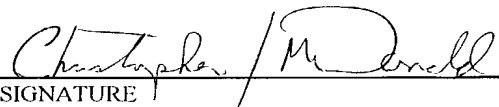
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**Christopher J. McDonald**  
 NAME

41,533  
 REGISTRATION NUMBER

25 January 2002  
 DATE

10030128 051502  
10/030128  
531 Rec'd PCT/ 25 JAN 2002

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the application of:

**Raffaele TOMELLERI**

Serial No:

Filed :

For : METHOD AND DEVICE FOR CORRECTING  
TOOL POSITION ERRORS IN MACHINE  
TOOLS

PRELIMINARY AMENDMENT

Commissioner of Patents and Trademarks  
Washington, DC 20231  
ATTN: BOX PCT

Sir:

Prior to the examination of the application, please  
amend the application as follows:

In the Claims:

Please amend claims 2-30 as shown on the marked-up  
claims. A copy of all pending claims is enclosed.

REMARKS

The Preliminary Amendment places the claims in  
conformance with U.S. practice.

Respectfully submitted,

by   
Christopher J. McDonald, Reg. 41,533

January 25, 2002

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Attorney's Docket: A-7769.PAM/lat

## CLAIMS

1. A method for correcting tool position errors in machine tools, characterised by:
  - determining the at least partial difference, referred to at least one predetermined degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe,
  - converting said difference into a correction signal, and
  - using said correction signal to move the tool in accordance with that degree of freedom relative to its support structure, at a response rate at least double that of the machine.
2. A method as claimed in claim 1, further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical machining surface.
3. A method as claimed in claim 1, further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.
4. A method as claimed in claim 1, further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and its theoretical position.
5. A method as claimed in claim 1, further comprising determining said difference from corrections deduced from previous measurements on the workpiece.
6. A method as claimed in claim 1, further comprising determining the difference between the theoretical behaviour of the machine axes and the true behaviour deduced from measurements thereof.
7. A method as claimed in claim 1, further comprising determining the difference by calculating the tool position error given by structural yielding inferred from a knowledge of

real-time speed and acceleration, said error being deduced from previously measured masses, structural rigidities and machine response characteristics.

8. A method as claimed in claim 1, further comprising determining the difference by real-time reading of the error between the theoretical position and true position of the axis of each axis of the machine.

9. A method as claimed in claim 1, further comprising determining the difference by measuring the dynamic component of the tool position error, using high precision accelerometers positioned in proximity to the tool arbor.

10. A method as claimed in claim 1, further comprising determining the difference by absolute measurement of the true position of the tool in relation to its theoretical position imposed by the machine numerical control system.

11. A device for correcting tool position errors in machine tools comprising:

- at least one member for regulating the position of a tool having a tool support structure, acting according to at least one predetermined degree of freedom, said member being inserted into the tool support structure downstream the axes of the machine tool and having a response rate at least double that of the machine tool;
- means for determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe, and
- means for converting said difference into a control signal for said regulating member according to said degree of freedom.

12. A device as claimed in claim 11, further comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and the position of a point on the theoretical machining surface.

13. A device as claimed in claim 11, further comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.
14. A device as claimed in claim 11, further comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and its theoretical position.
15. A device as claimed in claim 11, further comprising at least one actuator acting in accordance with said degree of freedom is inserted into the tool support structure.
16. A device as claimed in claim 11, further comprising three non aligned actuators operable independently of each other are inserted into the tool support structure to realize three degrees of freedom of the regulating member.
17. A device as claimed in claim 11, further comprising three actuators acting parallel to each other are inserted between the machine support and the arbor support structure.
18. A device as claimed in claim 11, wherein said actuator consists of a double-acting hydraulic cylinder inserted into the tool support structure, which is formed in two parts between which axial disc springs are interposed.
19. A device as claimed in claim 15, wherein each actuator is fed via a hydraulic servo-valve, to which it is connected.
20. A device as claimed in claim 11, wherein said actuator is of piezoelectric type.
21. A device as claimed in claim 11, wherein said means for determining the difference consist of signals made available by the machine numerical control system.

22. A device as claimed in claim 11, wherein said means for determining the difference consist of sensors for sensing the dynamic actions to which the component structures of the machine are subjected during machining.
23. A device as claimed in claim 11, further comprising at least one accelerometer for determining the dynamic component of the error between the true position of the arbor support and its theoretical position.
24. A device as claimed in claim 23, wherein the accelerometer is positioned downstream of the corresponding actuator.
25. A device as claimed in claim 11, further comprising feedback means for the correction measurement.
26. A device as claimed in claim 11, wherein said regulating member consists of a rotary axis of the tool carrying head.
27. A device as claimed in claim 11, wherein said regulating member consists of the axially traversable tool carrying structure.
28. A device as claimed in claim 27, wherein the arbor carrying structure is supported by two laminas and is associated for its traversing movements with an actuator of high response rate.
29. A device as claimed in claim 11 wherein said regulating member comprises a rotary axis provided with means for its orientation such that the correction has useful component against a predetermined profile.
30. A device as claimed in claim 11 further comprising:

- a first pair of laminas for connecting the structure, downstream the axis of the machine, to a first part,
- a second pair of laminas for connecting said first part to a second part forming the support of the tool,
- a first actuator placed between said structure and said first part,
- a second actuator placed between said first part a said second part.



## CLAIMS

1. A method for correcting tool position errors in machine tools, characterised by:
  - determining the at least partial difference, referred to at least one predetermined degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe,
  - converting said difference into a correction signal, and
  - using said correction signal to move the tool in accordance with that degree of freedom relative to its support structure, at a response rate at least double that of the machine.
2. A method as claimed in claim 1, [characterised by] further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical machining surface.
3. A method as claimed in claim 1, [characterised by] further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.
4. A method as claimed in claim 1, [characterised by] further comprising determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and its theoretical position.
5. A method as claimed in claim 1, [characterised by] further comprising determining said difference from corrections deduced from previous measurements on the workpiece.
6. A method as claimed in claim 1, [characterised by] further comprising determining the difference between the theoretical behaviour of the machine axes and the true behaviour deduced from measurements thereof.
7. A method as claimed in claim 1, [characterised by] further comprising determining

the difference by calculating the tool position error given by structural yielding inferred from a knowledge of real-time speed and acceleration, said error being deduced from previously measured masses, structural rigidities and machine response characteristics.

8. A method as claimed in claim 1, [characterised by] further comprising determining the difference by real-time reading of the error between the theoretical position and true position of the axis of each axis of the machine.

9. A method as claimed in claim 1, [characterised by] further comprising determining the difference by measuring the dynamic component of the tool position error, using high precision accelerometers positioned in proximity to the tool arbor.

10. A method as claimed in claim 1, [characterised by] further comprising determining the difference by absolute measurement of the true position of the tool in relation to its theoretical position imposed by the machine numerical control system.

11. A device for [implementing the method claimed in one or more of claims 1 to 10, characterised by] correcting tool position errors in machine tools comprising:

- at least one member for regulating the position of [the] a tool having a tool support structure, acting according to at least one predetermined degree of freedom, said member being inserted into the tool support structure [(10, 12, 54)] downstream the axes of the machine tool and having a response rate at least double that of the machine tool;
- means for determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe, and
- means for converting said difference into a control signal for said regulating member according to said degree of freedom.

12. A device as claimed in claim 11, [characterised by] further comprising means for determining the at least partial difference, referred to said degree of freedom, between the

true position of the tool and the position of a point on the theoretical machining surface.

13. A device as claimed in claim 11, [characterised by] further comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.

14. A device as claimed in claim 11, [characterised by] further comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and its theoretical position.

15. A device as claimed in claim 11, [characterised in that] further comprising at least one actuator [(16,38,56,63,68)] acting in accordance with said degree of freedom is inserted into the tool support structure [(10,12,54)].

16. A device as claimed in claim 11, [characterised in that] further comprising three non aligned actuators [(16)] operable independently of each other are inserted into the tool support structure to realize three degrees of freedom of the regulating member.

17. A device as claimed in claim 11, [characterised in that] further comprising three actuators [(16)] acting parallel to each other are inserted between the machine support [(10)] and the arbor support structure [(12)].

18. A device as claimed in claim 11, [characterised in that] wherein said actuator [(16)] consists of a double-acting hydraulic cylinder inserted into the tool support structure, which is formed in two parts between which axial disc springs [(20)] are interposed.

19. A device as claimed in claim 15, [characterised in that] wherein each actuator [(16)] is fed via a hydraulic servo-valve [(22)], to which it is connected.

20. A device as claimed in claim 11, [characterised in that] wherein said actuator is of piezoelectric type.
21. A device as claimed in claim 11,[ characterised in that] wherein said means for determining the difference consist of signals made available by the machine numerical control system.
22. A device as claimed in claim 11, [characterised in that] wherein said means for determining the difference consist of sensors for sensing the dynamic actions to which the component structures of the machine are subjected during machining.
23. A device as claimed in claim 11, [characterised by] further comprising at least one accelerometer for determining the dynamic component of the error between the true position of the arbor support and its theoretical position.
24. A device as claimed in claim 23, [11, characterised in that] wherein the accelerometer is positioned downstream of the corresponding actuator.
25. A device as claimed in claim 11, [characterised by] further comprising feedback means [(44,58,64,68)] for the correction measurement.
26. A device as claimed in claim 11, [characterised in that] wherein said regulating member consists of a rotary axis of the tool carrying head.
27. A device as claimed in claim 11, [characterised in that] wherein said regulating member consists of the axially traversable tool carrying structure.
28. A device as claimed in claim 27, [characterised in that] wherein the arbor carrying structure [(24)] is supported by two laminas [(26,28)] and is associated for its traversing movements with an actuator [(38)] of high response rate.

29. A device as claimed in claim 11 [suitable for machining a predetermined profile in a plane, characterised in that] wherein said regulating member [consists of] comprises a rotary axis provided with means for its orientation such that the correction has useful component against [said] a predetermined profile.

30. A device as claimed in claim 11 [suitable to plane working according to a prefixed outline characterised in that said member for regulating comprises] further comprising:

- a first pair of laminas [(61,62)] for connecting the structure [(10)], downstream the axis of the machine, to a first part [(60)],
- a second pair of laminas [(65,66)] for connecting said first part [(60)] to a second part [(12)] forming the support of the tool,
- a first actuator placed between said structure [(10)] and said first part [(60)],
- a second actuator placed between said first part [(60)] a said second part [(12)].

## METHOD AND DEVICE FOR CORRECTING TOOL POSITION ERRORS IN MACHINE TOOLS

This invention relates to a method and device for correcting tool position errors in machine tools.

- 5 In machine tools in general, and in milling machine in particular, an often substantial operational error can arise between the theoretical position of the tool relative to the workpiece and its true position.

This error, which overall can be defined as a geometrical error, derives from two contributions, namely the position error of a reference point on the  
10 tool (for example the centre of the tool sphere in the case of a spherical tool, or the end of the axis of a cylindrical tool) and the error in the tool orientation relative to its theoretical orientation. This invention is essentially aimed at reducing the tool position error which occurs both statically and during movement of its axes, however the invention also enables its orientation to be  
15 corrected.

Reducing the tool position error is of fundamental importance as it enables machining quality to be improved while at the same time achieving a greater speed and acceleration, hence reducing machining times and costs.

- In particular, reducing the position error in milling machines dedicated  
20 to mould machining is very important both for improving precision and for reducing manual polishing work, which involves considerable time and cost, with uncertain results.

Whatever the type of error, it is well known that tool position and orientation errors are present both statically, during low speed and low  
25 acceleration machining, and dynamically, during high speed and high acceleration machining.

For all these reasons it is extremely important to reduce as much as possible the error arising in any machine tool during operation, to which end machine tool designers and manufacturers devote considerable effort during the design stage in studying the dynamic characteristics of the axes and the machine structure, reducing the machining parameters and optimizing the control systems for the axes on the basis of their parts of travel, the arbor power and the weight of the workpiece and accessories.

Known solutions therefore involve the need to handle considerable masses, which limit the intrinsic axis frequencies and the intrinsic structural frequencies to values between about 10 Hz and 50 Hz in relation to the travel paths and weights of the moving parts. In their turn these low frequencies limit the performance obtainable with numerical control and in particular limit the space cycle gain and other connected parameters, resulting in limits on the obtainable precision, which is lower the higher the speed and acceleration during machining.

Machine in the form of a hexapod have recently been constructed, which rigidly support the arbor with lower structural masses. They increase the intrinsic machine frequencies, but at the same time they pose considerable limits on machining because of the particular type of machine.

The main object of the invention is to correct tool position errors in machine tools, in order to achieve high speed and acceleration of the moving parts with simultaneous high precision, without posing substantial limits on machine performance and without introducing constructional complexity.

A further object is to correct in open cycle the position error read on the machine axes, in addition to the centrifugal component of the tool position

error deduced from the masses and rigidity of the structure in the various directions.

5 A further object of the invention is to correct the tool position by taking account of the error between the true tool position and the true position of the axes, and to hence further reduce the error between the actual position and theoretical position of the tool.

10 A further object of the invention is to drastically reduce the static error on reversing movement, due to reversal response delays deriving from friction forces, and to substantially improve the statistical values of the axis positioning precision.

A further object of the invention is to correct the tool orientation.

A further object of the invention is to make it possible at any moment to test the arbor behaviour in the three directions at different frequencies, on the basis of the position of the axes.

15 A further object of the invention is to increase machine dynamic rigidity during power chip removal machining, so reducing machining chatter and considerably raising the machine removal limits, while allowing continuous monitoring of the amplitude of arbor vibrations deriving both from chatter and from tool unbalance, with possible indication if limits are exceeded or with  
20 automatic adjustment of machining parameters.

A further object of the inventions is to allow measurement of the tool force based on the already measured arbor rigidity, so enabling the tool intactness and its state of wear to be verified and to correct any deformations induced in the machine.

25 A further object of the invention is to allow closed cycle monitoring of the tool position when using very rapid and precise measurement systems



which indicate the tool position instantaneously and with high precision during machining, and including monitoring of the dynamic deformations to which it is subjected.

A further object of the invention is to make the correction using axes of  
5 heads provided for other purposes, in order thereby to effect the position correcting action.

All these and further objects which will be apparent from the ensuing description are attained, according to the invention, by a method for correcting tool position errors as described in claim 1.

10 The invention also comprises a device for correcting tool position errors in machine tools as described in claim 11.

A preferred embodiment of the invention is described in detail hereinafter with reference to the accompanying drawings, on which:

Figure 1 is a schematic view of a milling machine with its tool movable in  
15 accordance with three degrees of freedom and provided with the correction device of the invention.

Figure 2 is a partly sectional enlarged schematic view of the correction plate interposed between the machine and the tool arbor,

Figure 3 is a schematic front view of the correction plate,

20 Figure 4 is an enlarged sectional detail of an actuator for the correction plate,

Figure 5 is a schematic view of the machine of Figure 1 connected to a correction circuit relative to one degree of freedom,

Figure 6 shows four wave forms illustrating the invention of the correction  
25 device,

- Figure 7 shows a second embodiment of the correction device of the invention relative to one degree of freedom applied to a milling machine.
- Figure 8 shows a third embodiment of the correction device of the invention relative to two degrees of freedom, using a double rotatable head of quick response,
- Figure 9 shows a fourth embodiment of the correction device of the invention relative to one degree of freedom, usable for example in the laser cutting of plate metal,
- Figure 10 shows the correcting action in machining a surface of different types in space,
- Figure 11 shows the correcting action in machining a surface of different types in a plane, and
- Figure 12 shows a fifth embodiment of the correction device of the invention relative to two degrees of freedom, usable for example in laser cutting of plate metal.

As can be seen from the figures, the device of the invention can be applied to all types of machine tools, including those of traditional type, and comprises, preferably in proximity to the tool (it is less easy on the workpiece given its weight and dimensions), an active system having a response readiness and accuracy much higher than those of the machine and able to undergo movements in order to correct the position and possibly also the orientation of the tool relative to the workpiece.

What essentially distinguishes the device of the invention from traditional devices is the fact that it reduces tool position errors by tool correction movements (correction axes) having action components in those

directions already present on the machine axes (principle movement axes). Hence the machine degrees of freedom are repeated in the device of the invention, which moves in the same direction as the principle machine axes which are to be corrected, these correction movements being of very short  
5 travel aimed at correcting the residual error, with all the advantages which will become apparent hereinafter.

If these axes are also present for other purposes, such as in the case of heads with one or more rotary axes, and they are sufficiently fast, they can be used for the correction function, without adding further axes.

10 However, whereas the principal machine axes cover the entire field of work, and are therefore heavy and slow, the correction axes of the device of the invention, which moves the tool in the same directions, have travel limited to the extent of the correction and, as very small masses are involved in the movement, they achieve for the aforesaid reasons extremely quick response  
15 and a very small residual error.

Figure 1 schematically shows a milling machine to which a device of the invention is applied. The machine comprises a carriage 2 movable along the X axis along a fixed bed 4 and supporting an upright 6, along which a bracket 8 can support along the Z axis.

20 The bracket 8 supports, slidable along the Y axis, a slide support 10 at the end of which the tool arbor support 12 is mounted.

The unit which implements the device of the invention is interposed between the support 10 and the tool arbor support 12.

In the illustrated embodiment it consists of a plate 14 in which three  
25 identical double-acting hydraulic cylinders 16 are housed with their axes parallel. Two of these cylinders are positioned at the same lower level, the

third being positioned at a higher level (see Figure 3). They interface with a plate 18 of the tool arbor support 12, between them and the arbor support there being interposed three axial disc springs 20, their purpose being to enable only the three required movements to be made, without allowing lateral  
5 translation or axial rotation.

The three hydraulic cylinders are independently fed via quick-response servo-valves 22, which enable the plate 18 to move such as to implement the tool correction movements in the three directions.

Specifically, opposing movement of the upper actuator 16 and the two  
10 lower actuators 16 causes the plate 18 to rotate about the X axis and consequently cause the tool to undergo movements in the direction of the X axis. Opposing movement of just the two lower actuators 16 causes the plate 18 to rotate about the Z axis and consequently cause the tool to undergo correction movements in the direction of the X axis. Simultaneous concordant  
15 movement of the three actuators 16 causes the plate 18 and hence the tool to traverse in the direction of the Y axis.

The rigidity of the springs and of the oil present in the actuators, the mass of the arbor support 12 and the response rapidity of the servo-valves 22 enable very high pass-bands of greater than 50 Hz to be achieved for the  
20 system which moves the arbor support relative to the support 10.

Other embodiments are also possible, using different types of actuators (servo-motors, piezoelectric devices, etc.) able to implement the movements with different linkages (direct action, screws and balls, etc.)

The principle on which the operation of the device of the invention is  
25 based is apparent from Figure 5. In this it can be seen that with reference to the type of correction made, and regarding for ease of representation only the

X axis, in an infinitely rigid machine if  $X_0$  is the coordinate of the controlled theoretical position,  $X_a$  is the true coordinate of the X axis and  $X_u$  is the true coordinate of the tool, the position error of the axis and of the tool relative to the direction is given by  $X_{a0} = X_0 - X_a = X_0 - X_u$ .

- 5           The signal  $X_{a0}$  is processed by the device hardware, to provide the actuators 16 of the correction device with the appropriate commands to cause the true value of the coordinate  $X_u$  to coincide with the theoretical value  $X_0$ .

Figure 6 is the theoretical graph showing the variation of the movement component along the X axis with time. Figure 6a shows the  
10   theoretical variation. Figure 6b shows the true variation, which differs from the theoretical variation by virtue of the errors of the control system. Figure 6c shows the variation of the correction signal, which is determined instantaneously by comparison between the theoretical position and the true position of the axis. Figure 6d shows the corrected variation of the tool  
15   movement component in the X direction, which is substantially similar to the theoretical variation because of the very rapid and accurate response of the correction device.

It is apparent that the foregoing, which was limited to the X coordinate for reasons of descriptive clarity, is also valid for the other  
20   coordinates in spatial corrective action, which can be either total or partial.

In the foregoing example, the extent of the correction to be applied, ie the information to be fed to the system for processing the correction signal, is obtained as the difference between the value of the theoretical coordinate  $X_0$  and the value of the true coordinate  $X_a$ .

- 25           However, other criteria for acquiring the information necessary for the correction can be used. For example, the following can be used:

- corrections deduced from previous measurements made on the workpiece,
- corrections to the behaviour of the machine axes deduced by their measurement,
- calculation of the tool position error given by structural yielding inferred from a knowledge of real-time speed and acceleration, the error deduced from previously acquired machine response and yielding characteristics,
- real-time reading of the position error between the theoretical position and true position of the principle machine axes,
- measurement of the dynamic component of the tool position error, measured for example using high precision accelerometers positioned in proximity to the arbor,
- absolute measurement of the true position of the tool in relation to its theoretical position imposed by numerical control, inferred from direct measurement device, as for example laser interferometer.

Figure 7 shows a correction device of the invention which uses an electro-arbor 24 supported by two laminas 26 and 28 secured to it by rings 30 and 32 respectively. Said laminas are fixed to the support 10, downstream the machine axes by a further two rings 34 and 36 such that the electro-arbor 24 can undergo axial movements of an extent sufficient to make the dynamic correction.

This dynamic correction is effected by a suitable actuator 38 of hydraulic, piezoelectric or other type, secured to the support 10 by a fixed bracket 40, to axially move the electro-arbor by a movable bracket 42, with suitable feedback by a transducer 44.

This corrective action can also be provided in a different manner via one or more axes already existing in the machine for other functions, as for

example in the case of those heads with one or more axes provided to suitably orientate the tool during machining. In this case the invention is implemented by providing the head axis or axes with rapid response so that they can be used to at least partially correct the position errors of the principle  
5 machine axes.

For example, Figure 8 shows a double rotatable head of right-angled type having a first part 48, rotating with respect to the support 10, downstream the machine axes and a second part 50 which supports the arbor. If one or both the axes have quick response motors, they can move in accordance with  
10 the two possible degrees of freedom and hence correct the position error in said two degrees of freedom. The correction is possible in this case on condition that the arbor axis is not perpendicular to the machining surface and is able to return the tool close to the surface using just one of the two axes, or onto the profile being machined using both the axes. The extent of the  
15 correction can be easily deduced once the true tool position, the surface position and the direction of action of the two axes are known.

When machining spatial surfaces, such as when machining moulds, the tool position error correction does not necessarily have to be total, in that to correct the machining error it is sufficient to return the tool to the theoretical  
20 surface or to its theoretical trajectory. In the specific case of machining profiles in a plane, it is sufficient to return the tool to its trajectory.

Consequently when speaking of tool position correction, this does not necessarily mean returning it to its theoretical position, but rather returning it to its geometrical machining locus.

25 Moreover, as the correction can be total or partial, tool position correction generally means identifying the distance of the tool from the

geometrical machining locus either on a surface in space or on a trajectory in a plane.

Figure 9 shows a correction device of the invention used in machining in a plane, for example with a laser cutting device 52 fixed to a rotary arm 54 supported by the support 10. The arm 54 is rotated by a quick-response motor 56 with suitable feedback by the rotary transducer 58. The arm 54 has to be able to rotate through about 90 degrees, and by being angularly rotated slowly in a suitable manner it is always possible to apply corrective action when the direction of the tangent to the profile varies. The arm orientation angle is transmitted to the numerical control system which corrects the position of the axes in relation to the angle assumed.

Figure 10 shows the machining of a profile "p" in a plane. It shows the theoretical point  $P_0$  and the true point P affected by the errors  $\Delta x$  and  $\Delta y$ .

The corrective action can follow the path "a", which completely corrects the error but requires two actuators, or it can follow the path "b", with a movement allowed by a single actuator, or it can follow the path "c", which is the minimum distance path and requires either two actuators or preliminary orientation of the corrective action of a single actuator.

Figure 11 shows the machining of a surface in space. It shows the theoretical point  $P_0$ , the true point P affected by the errors  $\Delta x$ ,  $\Delta y$  and  $\Delta z$ , the machining path  $p_0$  and the paths  $p_1$ ,  $p_2$  and  $p_3$ , which are sections through the surface on planes parallel to the machining plane  $p_0$ . the corrective action to return the tool to the machining path  $p_0$  can be applied along the path "a" using three actuators, or along the path "b" using two actuators, or along the path "c" using three actuators which however return the tool not to the point  $P_0$  but to the closest position along the path  $p_0$ , or along the path "d" to return



the tool to the surface and specifically to the path p1 using a single actuator, or finally along the path "e" which uses two actuators and which returns the tool to the surface and specifically to the path p2, with the shortest correction.

Figure 12 shows an alternative embodiment of correction on two size  
5 machines as those for cutting plate metal, with correcting action along two degrees of freedom. The support 10 is placed downstream the axes of the machine and supports the part 60 by two laminas 61 or 62 enabling correction movements along the X axis through an actuator 63 and a measurement transducer 64. On its turn, through other laminas 65 and 66, an actuator 67  
10 and a feed-back transducer 68 the correction movement of the support 12 of the tool is obtained along the Y axis, or of the laser cutting device 52 or other operating unit.

From the foregoing it is apparent that the method and device of the invention fully attain the stated objects, and in particular:

- 15 - they enable tool position errors to be corrected in machine tools while attaining high speed and acceleration of the moving parts and at the same time high precision, without substantial limits on the machine performance and without constructional complexity;
- they correct these errors with very small movements of the axes of the  
20 correction device, of generally less than one millimetre. Consequently the corrections which can be established with degrees of freedom not necessarily equal to that of the machine, don't require actual guides but may utilize very compact and economical solutions, such as solutions involving flexible laminas: the actuators for the movements can also be very  
25 compact, using hydraulic cylinders or piezoelectric actuators;

- they involve very small clearances and great rigidity, and as they practically add no mass to the system they enable considerable dynamic performance to be obtained;
- they limit the action stroke of the correction device to the extent of the residual error of the principle axes, and although this means that methods must be used to measure this residual error, at the same time they limit the width of the correction action and hence reduce the residual error to a minimum after correction;
- if they use arrangements for directly measuring the tool position, for example laser interferometers or laser tracking, they enable direct calculation of the error to be made, so precisely defining the corrective action;
- because of the small extent of the corrective action, the reaction movements induced in the support structure for the correction device are of practically negligible extent;
- in the case of a machine tool provided with supplementary rotational axes, such as rotatable or double rotatable heads provided to suitably orientate the tool in relation to the surface, these same axes, if given sufficiently fast response, can be used to provide the necessary corrective action, considering that the movements required for the correction do not appreciably alter tool orientation;
- they allow open cycle correction of the position error read on the machine axes, in addition to the structure centrifugal component deduced from its rigidity in the various directions;
- they enable the tool position to be corrected by taking account of the dynamic deformation of the structure, or of the error between the position of

the tool and the position of the axes, and to hence further reduce the error between the actual position and theoretical position of the tool;

- they drastically reduce the static error arising during movement reversal, due to reversal response delays deriving from friction forces, and
- 5 substantially improve the statistical values of the axis positioning precision;
- they enable tool orientation to be corrected;
- they make it possible at any moment to test the arbor behaviour in the three directions at different frequencies, on the basis of the position of the axes, by operating the actuators at the different frequencies to hence stress the
- 10 machine by inertial forces in the different directions;
- they considerably increase machine dynamic rigidity during power chip removal machining, so reducing machining chatter and considerably raising the machine removal limits, while allowing continuous monitoring of the amplitude of arbor vibrations deriving both from chatter and from tool
- 15 unbalance, with possible indication if limits are exceeded a with automatic adjustment of machining parameters;
- they allow measurement of the tool force based on the arbor rigidity already known from response spectra, so enabling the tool intactness and its state of wear to be verified, and to correct any deformations induced in the
- 20 machine;
- they enable the tool position to be continuously corrected during its rotation, with very precise upward or downward correction of the hole diameter and shape during boring.

## C L A I M S

1. A method for correcting tool position errors in machine tools, characterised by:
  - determining the at least partial difference, referred to at least one
  - 5 predetermined degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe,
  - converting said difference into a correction signal, and
  - using said correction signal to move the tool in accordance with that degree of freedom relative to its support structure, at a response rate at least
  - 10 double that of the machine.
2. A method as claimed in claim 1, characterised by determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical machining surface.
- 15 3. A method as claimed in claim 1, characterised by determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.
4. A method as claimed in claim 1, characterised by determining the at
- 20 least partial difference, referred to said one degree of freedom, between the true position of the tool and its theoretical position.
5. A method as claimed in claim 1, characterised by determining said difference from corrections deduced from previous measurements on the workpiece.

6. A method as claimed in claim 1, characterised by determining the difference between the theoretical behaviour of the machine axes and the true behaviour deduced from measurements thereof.
7. A method as claimed in claim 1, characterised by determining the  
5 difference by calculating the tool position error given by structural yielding inferred from a knowledge of real-time speed and acceleration, said error being deduced from previously measured masses, structural rigidities and machine response characteristics.
8. A method as claimed in claim 1, characterised by determining the  
10 difference by real-time reading of the error between the theoretical position and true position of the axis of each axis of the machine.
9. A method as claimed in claim 1, characterised by determining the difference by measuring the dynamic component of the tool position error, using high precision accelerometers positioned in proximity to the tool arbor.
- 15 10. A method as claimed in claim 1, characterised by determining the difference by absolute measurement of the true position of the tool in relation to its theoretical position imposed by the machine numerical control system.
11. A device for implementing the method claimed in one or more of claims 1 to 10, characterised by comprising:
- 20 - at least one member for regulating the position of the tool, acting according to at least one predetermined degree of freedom, said member being inserted into the tool support structure (10, 12, 54) downstream the axes of the machine and having a response rate at least double that of the machine;

- means for determining the at least partial difference, referred to said one degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe, and
- means for converting said difference into a control signal for said regulating member according to said degree of freedom.

12. A device as claimed in claim 11, characterised by comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and the position of a point on the theoretical machining surface.

13. A device as claimed in claim 11, characterised by comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and the position of a point on the theoretical trajectory which the tool should describe.

14. A device as claimed in claim 11, characterised by comprising means for determining the at least partial difference, referred to said degree of freedom, between the true position of the tool and its theoretical position.

15. A device as claimed in claim 11, characterised in that at least one actuator (16,38,56,63,68) acting in accordance with said degree of freedom is inserted into the tool support structure (10,12,54).

16. A device as claimed in claim 11, characterised in that three non aligned actuators (16) operable independently of each other are inserted into the tool support structure to realize three degrees of freedom of the regulating member.

17. A device as claimed in claim 11, characterised in that three actuators (16) acting parallel to each other are inserted between the machine support (10) and the arbor support structure (12).

18. A device as claimed in claim 11, characterised in that said actuator (16) consists of a double-acting hydraulic cylinder inserted into the tool support structure, which is formed in two parts between which axial disc springs (20) are interposed.
- 5 19. A device as claimed in claim 15, characterised in that each actuator (16) is fed via a hydraulic servo-valve (22), to which it is connected.
20. A device as claimed in claim 11, characterised in that said actuator is of piezoelectric type.
21. A device as claimed in claim 11, characterised in that said means for  
10 determining the difference consist of signals made available by the machine numerical control system.
22. A device as claimed in claim 11, characterised in that said means for  
15 determining the difference consist of sensors for sensing the dynamic actions to which the component structures of the machine are subjected during machining.
23. A device as claimed in claim 11, characterised by comprising at least one accelerometer for determining the dynamic component of the error between the true position of the arbor support and its theoretical position.
24. A device as claimed in claim 11, characterised in that the accelerometer  
20 is positioned downstream of the corresponding actuator.
25. A device as claimed in claim 11, characterised by comprising feedback means (44,58,64,68) for the correction measurement.
26. A device as claimed in claim 11, characterised in that said regulating member consists of a rotary axis of the tool carrying head.
- 25 27. A device as claimed in claim 11, characterised in that said regulating member consists of the axially traversable tool carrying structure.

28. A device as claimed in claim 27, characterised in that the arbor carrying structure (24) is supported by two laminas (26,28) and is associated for its traversing movements with an actuator (38) of high response rate.

29. A device as claimed in claim 11 suitable for machining a predetermined  
5 profile in a plane, characterised in that said regulating member consists of a rotary axis provided with means for its orientation such that the correction has useful component against said profile.

30. A device as claimed in claim 11 suitable to plane working according to a prefixed outline characterised in that said member for regulating comprises:

- 10 - a first pair of laminas (61,62) for connecting the structure (10), downstream the axis of the machine, to a first part (60),
- a second pair of laminas (65,66) for connecting said first part (60) to a second part (12) forming the support of the tool,
- a first actuator placed between said structure (10) and said first part (60),
- 15 - a second actuator placed between said first part (60) a said second part (12).



(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
1 February 2001 (01.02.2001)

PCT

(10) International Publication Number  
**WO 01/07975 A1**

(51) International Patent Classification<sup>7</sup>: **G05B 19/404**,  
B25J 9/16

(21) International Application Number: PCT/EP00/07166

(22) International Filing Date: 26 July 2000 (26.07.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
VE99A000033 27 July 1999 (27.07.1999) IT

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(81) Designated States (*national*): AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZA, ZW.

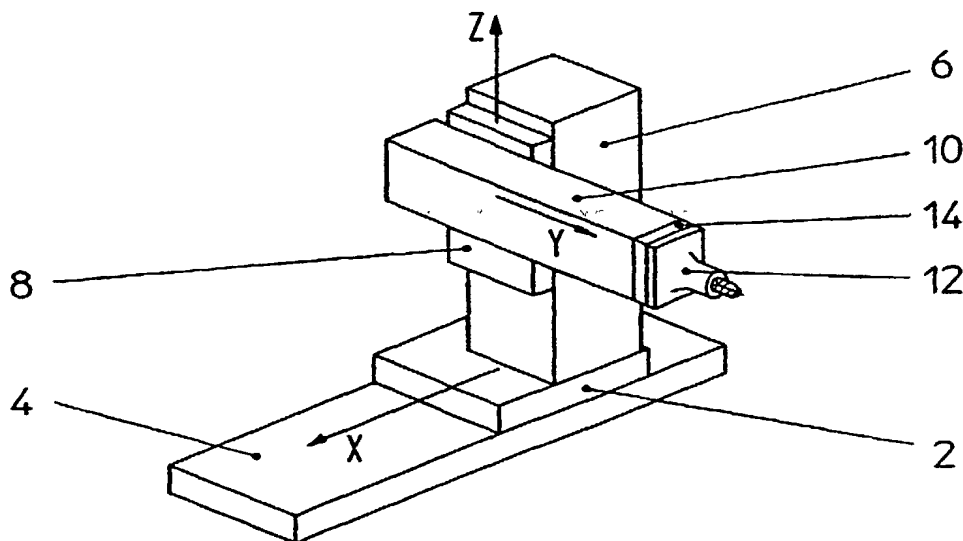
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

**Published:**

- With international search report.
- Before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments.

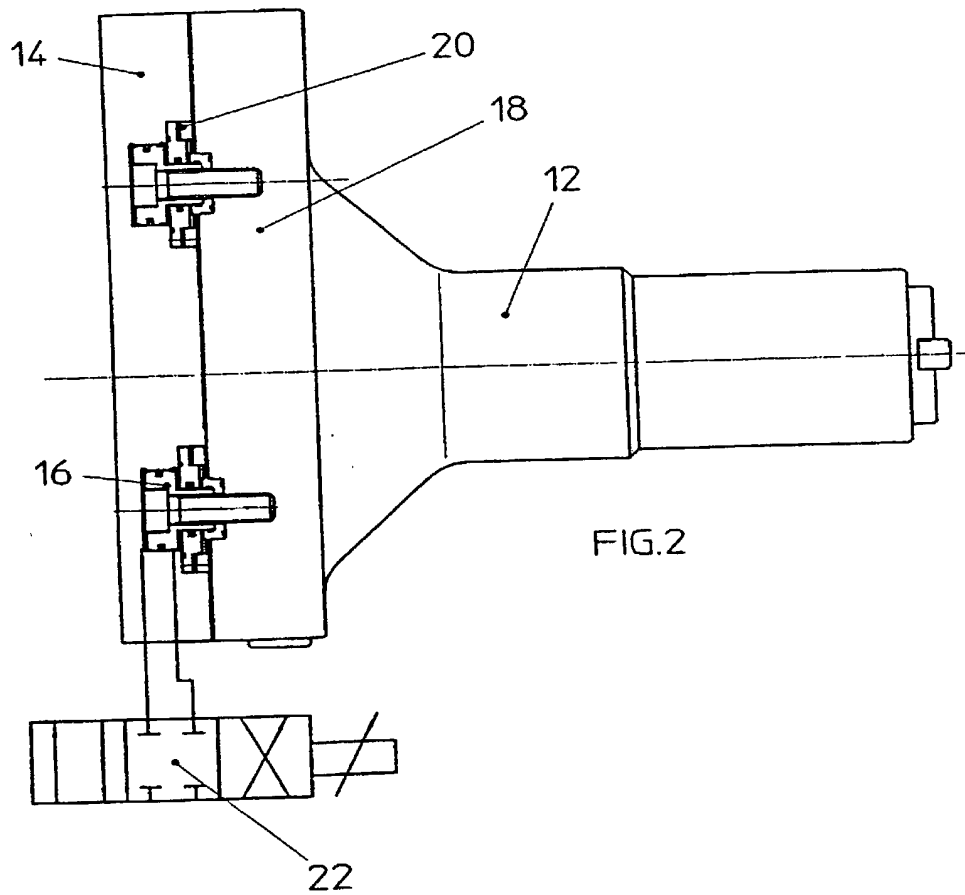
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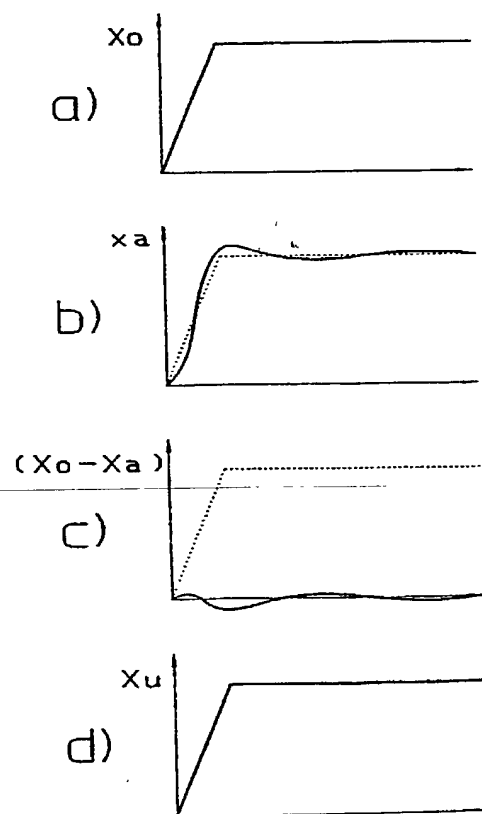
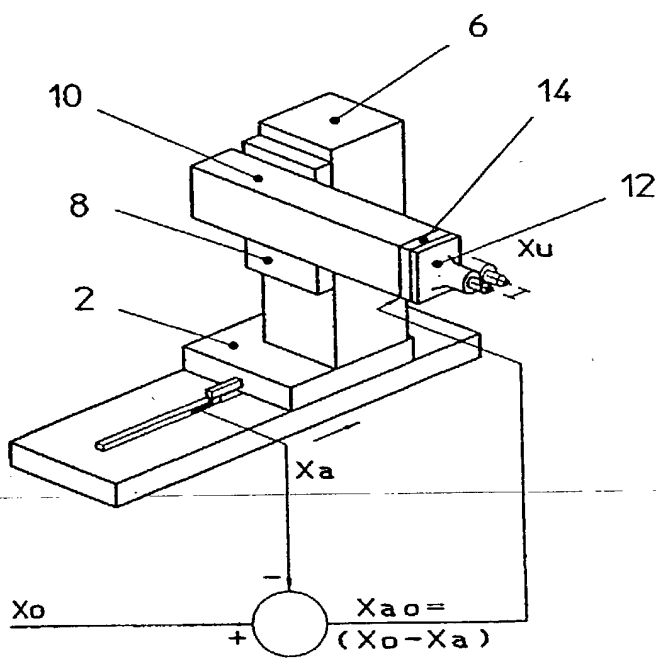
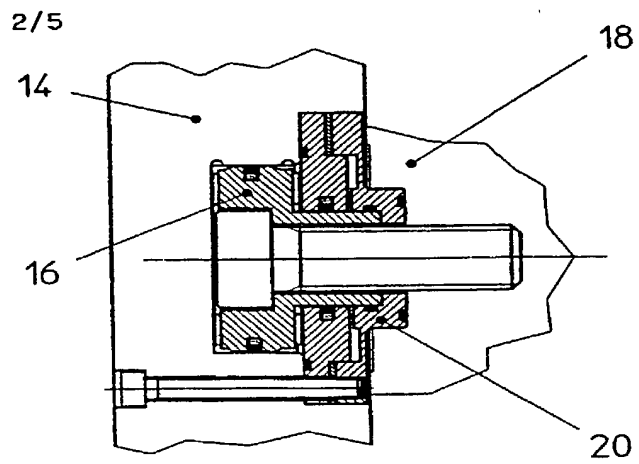
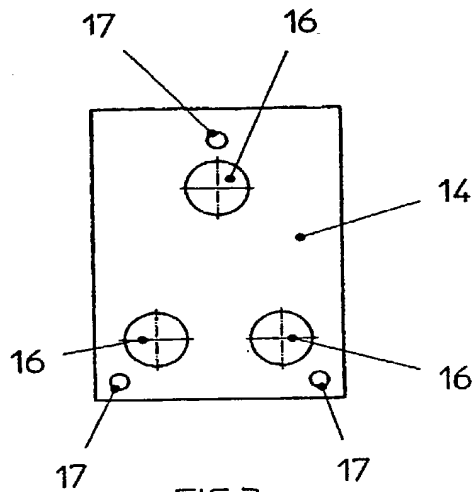
(54) Title: METHOD AND DEVICE FOR CORRECTING TOOL POSITION ERRORS IN MACHINE TOOLS



(57) Abstract: A method for correcting tool position errors in machine tools, characterised by: determining the at least partial difference, referred to at least one predetermined degree of freedom, between the true position of the tool and a point on the theoretical geometrical locus which the tool should describe, converting said difference into a correction signal, and using said correction signal to move the tool in accordance with that degree of freedom relative to its support structure, at a response rate at least double that of the machine.

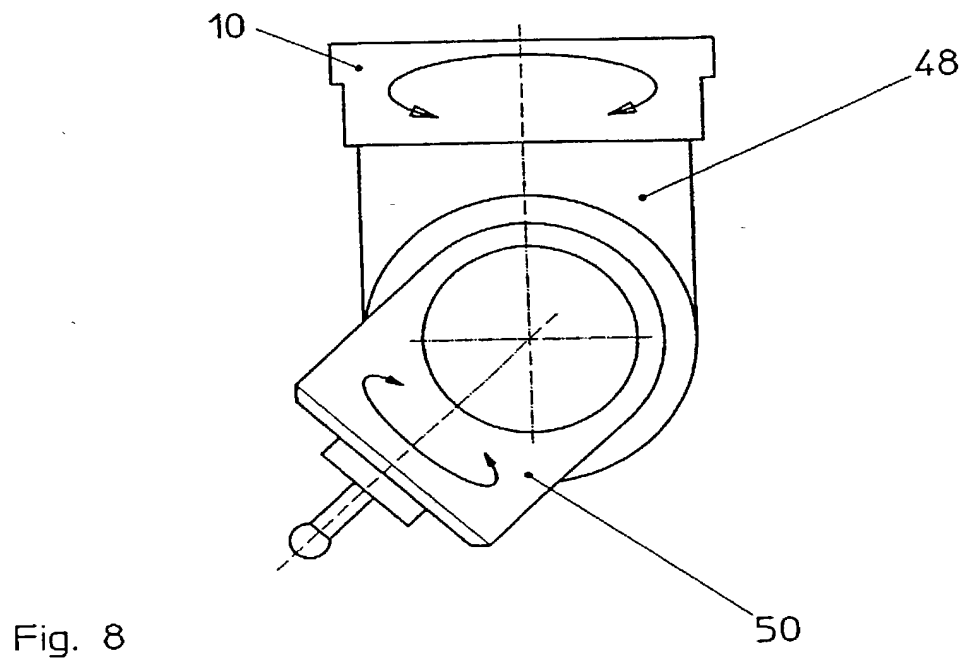
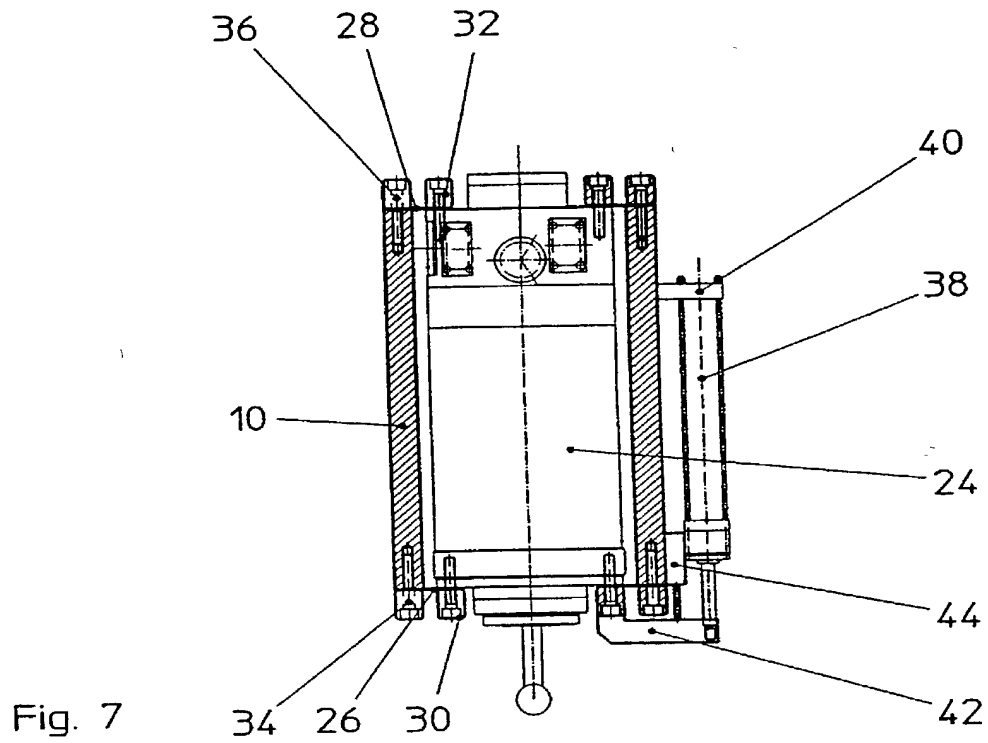
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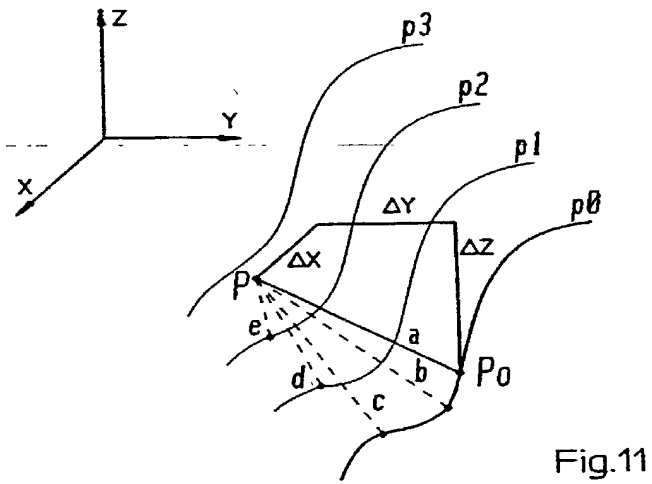
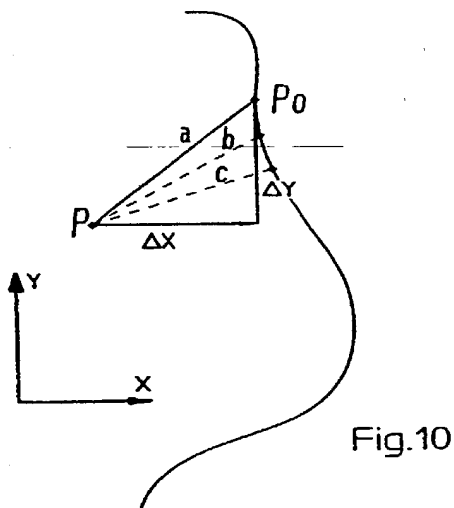
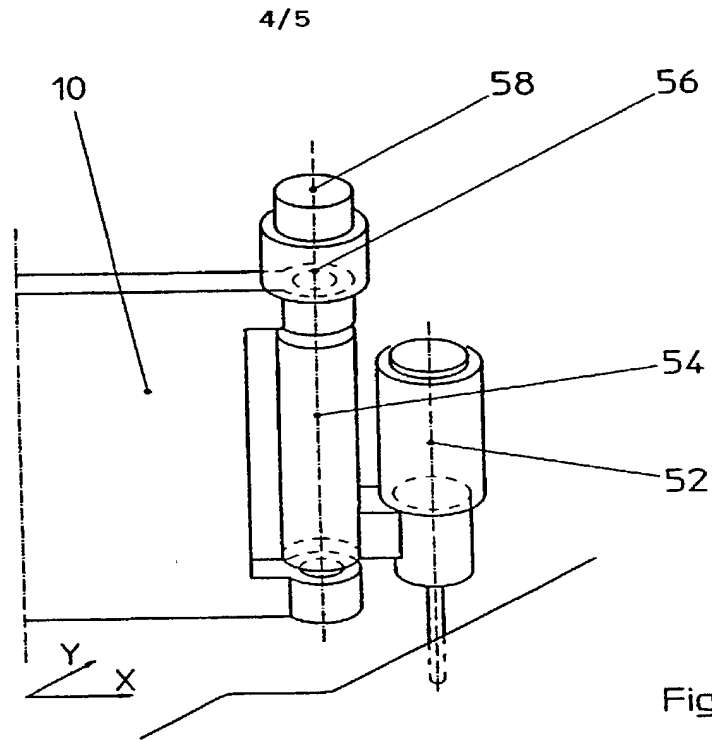




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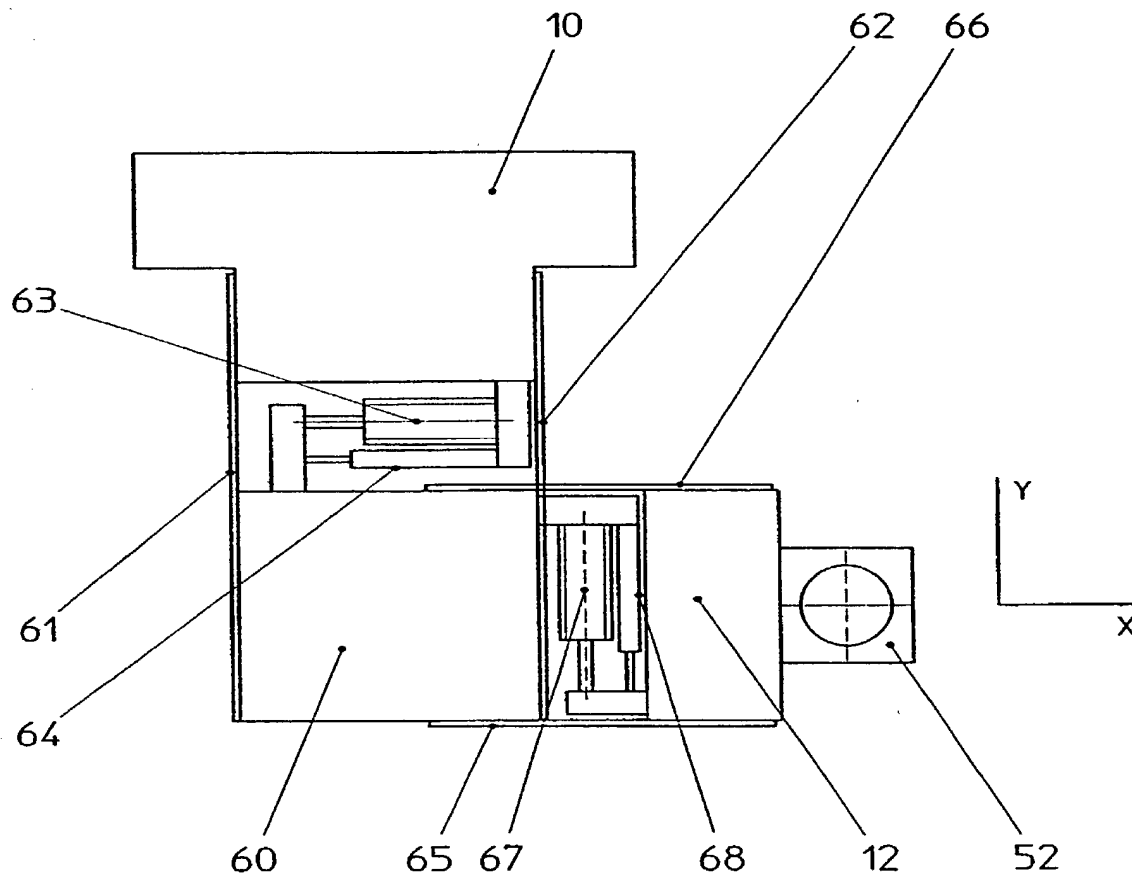


FIG.12



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A-7769

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Insert Title: Method and device for correcting tool position errors in machine tools.  
Fill in Appropriate Information - For Use Without Specification Attached: the specification of which is attached hereto. If not attached hereto, the specification was filed on January 25, 2002 as United States Application Number 10/030,128 and amended on \_\_\_\_\_ (if applicable) and/or the specification was filed on \_\_\_\_\_ as PCT International Application Number \_\_\_\_\_; and was amended under PCT Article 19 on \_\_\_\_\_ (if applicable)

I hereby state that I have reviewed and understand the contents of the above-identified specification, including the claims, as amended by any amendment referred to above.

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Prior Foreign Application(s)	Priority Claimed
VE99A000033 Italy 07.27.1999	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
(Number) (Country) (Month/Day/Year Filed)	
PCT/EP00/07166 PCT 07.26.2000	<input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
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Insert Prior U.S. Application(s): (if any)	(Application Number)	(Filing Date)	(Status - patented, pending, abandoned)

A-7769  
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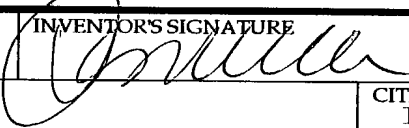
Insert Residence  
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Full Name of Second  
Inventor, if any:  
see above

Full Name of Third  
Inventor, if any:  
see above

Full Name of Fourth  
Inventor, if any:  
see above

GIVEN NAME/FAMILY NAME <u>Raffaele TOMELLERI</u>		INVENTOR'S SIGNATURE 	DATE* <u>25.01.02</u>
Residence (City, State & Country) <u>VERONA (ITALY) ITX</u>		CITIZENSHIP <u>Italian</u>	
MAILING ADDRESS (Complete Street Address including City, State & Country) <u>Via I Traversa Spiana, 7</u> <u>37138 - VERONA (ITALY)</u>			
GIVEN NAME/FAMILY NAME		INVENTOR'S SIGNATURE	DATE*
Residence (City, State & Country)		CITIZENSHIP	
MAILING ADDRESS (Complete Street Address including City, State & Country)			
GIVEN NAME/FAMILY NAME		INVENTOR'S SIGNATURE	DATE*
Residence (City, State & Country)		CITIZENSHIP	
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GIVEN NAME/FAMILY NAME		INVENTOR'S SIGNATURE	DATE*
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